PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Rotary Transformer for Coupling Multi-Phase Systems having a Small Frequency Difference

We, BROWN, BOVERI & COMPANY LIMITED, of Baden, Switzerland, a Swiss Company, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The standard type of rotary transformer for coupling a.c. power networks or systems consists of a synchronous machine which is connected to one system and coupled with a non-synchronous machine that is connected to the other system. A commutator machine, for instance a Scherbius or Lydall machine, is arranged in cascade with the non-synchronous machine. It serves to transmit the slip-power without loss and to control the active and reactive power of the non-synchronous machine. Generally it is coupled to the non-synchronous machine, it can, however, be arranged separately and coupled to an auxiliary machine. Such a rotary transformer, is very suitable for coupling a single-phase, $16\frac{2}{3}$ c/s railway system with a three-phase 50 c/s industrial system.

Naturally, such a rotary transformer can also be used when two systems having the same frequency, for example 50 c/s or 60 c/s, or frequencies that differ only slightly have to be connected together. The equipment is then, however, large and costly, because the two machines, namely the synchronous and non-synchronous machine, have to be dimensioned for the full through power. Furthermore, both machines have losses.

In accordance with the invention these disadvantages when interconnecting a.c. power distribution systems having only a slight frequency difference are avoided due to the connection being achieved by means of a single machine, namely a non-synchronous machine, the stator of which is connected to one system and the rotor to the other one and of which the poles number not more than four. Intermediate transformers can of course be provided. When the systems are in synchronism, the non-synchronous machine remains in the position in which the stator winding and the rotor winding are in phase with the associated systems. The non-synchronous machine then acts like a transformer. When the actual number of turns of the rotor and stator winding correspond to the transformation ratio of the voltage of one system to that of the other system, no active or reactive power is transmitted by the non-synchronous machine.

If the rotor is turned out of this position, active power occurs in the non-synchronous machine, so that the non-synchronous machine operates as a transformer. Power is transmitted from one system to the other. This power corresponds to a torque on the shaft of the non-synchronous machine. An auxliary machine may be used for turning the rotor. It can for instance be a direct-current machine. It is assumed that such a machine is coupled to the non-synchronous machine. The d.c. machine can for instance be coupled to at least one of the systems by a Ward-Leonard arrangement, i.e. a rotating converter or a stationary converter. When the d.c. machine is excited with a constant current, its armature current is a measure of its torque, according to magnitude and direction. The active power of the non-synchronous machine is proportional to this torque. When the two systems are no longer in synchronism, the rotor of the non-synchronous machine turns according to the frequency difference. The terminal voltage of the d.c. machine varies proportionally

with its speed. The direct-voltage supply has therefore to be increased correspondingly. Two functions can be performed by the d.c. machine:

a) Starting: In order to put the rotary transformer into operation, first of all the stator or rotor is switched in. Then the rotor is turned by the d.c. machine in such a manner that the voltage vector of the still disconnected part of the non-synchronous machine is in phase and synchronism with the associated system vector, whereupon switching-in can occur. This synchronisation can of course be achieved automatically.

b) Power regulation: The armature current of the d.c. machine is proportional to the through power of the rotary transformer. It is used for correcting the power in dependence on the magnitude and direction.

Instead of a d.c. machine, it is possible to use a non-synchronous machine preferably with a squirrel-cage rotor. There are various possibilities as regards supplying the non-synchronous machine, for instance by way of a low-frequency Scherbius machine or a static inverter. In any case it is an advantage to control the non-synchronous machine in such a manner that its flux is constant, so that by regulating its current it is possible to regulate the power of the inverter. The auxiliary machine can also be constructed as a frequency-controlled synchronous machine.

A particular advantage of our rotary transformer is that only a single machine has to be provided for the through rating and not two machines as has hitherto been the case. The efficiency is very high. A further advantage is the low speed of the transformer. It corresponds to the frequency difference of the two systems. The centrifugal forces acting on the rotor winding are thus small, generally negligible. The rotor can therefore have a large diameter and no difficulties are encountered as regards fixing the winding, so that it can be constructed practicaly like a stator winding. At least no special measures have to be taken in connection with the laminated rotor, keys, bandages etc., in order to check the effects of the centrifugal forces.

Our rotary transformers can be constructed for hitherto unattained powers, for instance 200 to 300 MW and more. The number of poles is chosen as small as possible, for instance $2p=2$ or 4. It is assumed that the power is 300 MW, the frequency 60 c/s and $2p=2$. A turbogenerator with such a power rating would have a rotor diameter of 1000 mm, where the centrifugal forces are already excessively high. For our rotary transformers the diameter can be much higher without taking any risks, for instance 2000 mm or more. In such a rotor the winding can be readily located. The laminated core and the stator and rotor winding can easily be cooled by modern means, for instance hydrogen gas or a liquid (e.g. water or oil). Water is preferable on account of its excellent cooling effect. Sealing problems hardly exist, especially because the moving part rotates very slowly.

Current is supplied to the rotor winding by way of slip-rings. Brushes having a low resistance, for instance with a high copper content, can be used because the frictional losses are very small at the low speed. The low peripheral speed of the slip-rings results in a very small brush wear. It is therefore possible to select a high voltage for the slip rings, for instance about 10,000 volts or more. The leakage paths between the slip-rings can be enlarged and separating walls provided. With a low speed, it is even possible to achieve a complete insulating separation, when a fixed part is allowed to be in direct sliding contact with a rotating part.

The power of the auxiliary machine in the embodiment of the invention under consideration would with a maximum difference of 2% between the frequencies of the systems amount to $300{,}000\times0.02=6000$ kW. The maximum speed would be 2% of the synchronous speed, that is $3600\times0.02=72$ r.p.m. Such a machine can easily be designed as a direct-current machine. It is similar to a rolling mill motor. The d.c. machine rotates in one or the other direction, depending upon whether the frequency difference is positive or negative. When the systems are in synchronism the machine is at a standstill. The brushes then remain on the same commutator-segments. This condition can last for several seconds. It may be desirable to rock the brushes as described below. The frequencies in both systems do not remain the same for any length of time, this being naturally on the assumption that there is no rigid coupling of the systems, a fact which does not, however, necessitate a flexible coupling. The aforementioned change in the frequency causes a rotation of the d.c. machine so that the segments move away from underneath the brushes. There are therefore no difficulties as regards the commutator.

In the succeeding description reference will be made to the accompanying drawings, in which:

Figure 1 shows schematically an embodiment of the invention, and

Figure 2 shows schematically an arrangement for stabilizing our rotary transformer.

The power balance-account of our rotary transformer is interesting and will be explained with the aid of Figure 1. System I having a frequency f_1 is coupled by means of the non-synchronous machine A with a system II having a frequency f_2. The rotor of this machine is mechanically coupled to a direct-current machine G having an exictation wind-

ing E. The d.c. machine is supplied by way of an inverter U which can be connected either to system I or to system II by means of a change-over switch.

For simplicity, the following calculation does not take any losses into account.

A power P flows from system I into the stator winding. The rotor of the non-synchronous machine rotates with a speed $n=\frac{60}{p}(f_1-f_2)$, p being the number of pole pairs. When $f_1=f_2$, $n=0$; that is, the rotor is at a standstill. The synchronous speed of the stator is $n_s=\frac{60}{p}f_1$ and the slip of the non-synchronous machine $s=\frac{n_s-n}{n}=\frac{f_2}{f_1}$. The rotor or slip power $s\times P=\frac{f_2}{f_1}\times P$ flows into system II. The difference between P and $s\times P$, that is $\frac{f_1-f_2}{f_1}\times P$, flows through the direct-current machine into system I or II, depending on the connection. When the power flow reverses, the arrows are also reversed moreover when $f_2>f_1$.

Based on the conditions shown in Figure 1, a phase rotation in the rotor in the direction of rotation of the stator field, that is in a mechanical sense, results in a power increase, a phase rotation in the opposite direction produces a power reduction.

In the embodiment described, two 60 c/s systems were connected. Naturally the conclusions which have been reached also apply when a 50 c/s system is coupled to a 60 c/s system.

In the example shown in Figure 1, the auxiliary machine is a direct-current machine. As already mentioned, it can be a non-synchronous or a synchronous machine. A smaller type of machine can be used if its speed is increased, for instance by using a speed gear.

The reactive power transmission can be altered by varying the transformation ratio between the voltages of both systems. The exchange of reactive power is controlled by altering the transformation ratio of one or more transformers which are connected either between the stator and one system or between the rotor and the other system.

Since it is not possible to produce reactive power with the rotary transformer, the reactive power is improved or regulated by a phase shifter of a capacitor battery in parallel with it on one or the other system.

The rotary transformer performs a rotation corresponding to the freqnency difference of the systems which is thus very slow. The current transfer between elements of the machine set can be achieved by various means. Primarily, brushes are used which are in sliding contact with the movable parts. Movable parts used for the current transfer are therefore the slip-rings of the rotary transformer or the commutator of the direct-current machine which serves as the auxiliary machine previously referred to.

When the systems are in synchronism with each other for a time and the through power of the rotary transformer is maintained constant, then the brushes will remain in the same position on the slip-rings and commutator respectively. The contact points can thus attain an excessive temperature. As a result, the slip-rings may become deformed and structural changes in the material can occur. This also applies to the commutator of the auxiliary machine where segments can suffer a radial displacement or be destroyed due to overheating. Slip-ring and commutator may assume an irregular shape and furthermore the brushes may be damaged.

This disadvantage can be avoided by causing the brushes to be moved back and forth. It is an advantage if the brushes are not always displaced to the same end positions. This can be achieved by using a device which serves to produce a periodic rotary motion of those parts of the machine on which the brushes are mounted, for instance the brush bridge. The brush bridges are connected with the output shaft of a differential gear that changes their position, and an input shaft to this gear is equipped with means for altering the central position of the brush bridge, a second input shaft to this gear being provided with means for effecting a periodic back and forth rotation with variable amplitude.

As regards the slip-rings of the non-synchronous machine, the brush bridge is caused to oscillate and flexible connections are provided for the brush holder. In the case of the commutator of the driving motor, its stator together with the brush bridge is caused to perform a back and forth movement and flexible leads are used for the connection to the stator.

The non-synchronous machine itself has no damping such as a synchronous machine has with its damping winding or due to its solid poles and pole shoes. Oscillations can therefore occur in the rotary transformer which become noticeable in the form of power oscillations with reference to the prescribed value. Particularly when the ohmic resistance of a network is relatively high, instability can occur, so that the rotary transformer has to be switched out. When the auxiliary machine is for instance a squirrel-cage motor which is supplied from controlled rectifiers, its shunt characteristic, that is speed-torque characteristic, has a stabilizing effect, but this is generally not sufficient.

To achieve adequate damping, which is independent of the type of auxiliary machine used, the oscillations are damped by controlling the auxiliary machine by means of a measured value of an operating parameter of the non-synchronous machine which is introduced into the regulating circuit of the auxiliary machine.

Figure 2 illustrates a schematic arrangement for thus preventing oscillations. The non-synchronous machine is indicated by A, its stator winding being connected to system I and its rotor winding to system II. The rotor is rigidly coupled for instance to a squirrel-cage motor M supplied from system I by way of an inverter W.

A measured value of an operating parameter of the machine A is used for stabilization, its deviation from a reference value being applied to the regulating circuit of the auxiliary machine. Suitable parameters the power (ΔP) of the rotary transformer, the torque (ΔT) of the non-synchronous machine A, the slip (Δs) of the latter, which corresponds to the speed deviation from the stationary rotor speed, and the load angle (δ), which describes the displacement of the rotor from the phase position corresponding to no-load to the phase position corresponding to the desired torque. These measured values are converted by a measure and converter H into corresponding electric signals and supplied by way of a common summation element S to the inverter W for the purpose of regulating the motor M.

Since the regulating process should occur rapidly, it is expedient to obtain a derivative of the measured value as a function of time and to use this value in the regulating circuit. One or more measured values can be utilized simultaneously in order to obtain the desired stabilization.

WHAT WE CLAIM IS:—

1. A rotary transformer of high power capacity for coupling multi-phase a.c. power distribution systems having approximately the same frequency, consisting of a non-synchronous machine of which the stator is connected to one of said systems and the rotor is connected to the other system and of which the number of poles is not greater than four.

2. A rotary transformer as claimed in claim 1 in which the rotor is connected mechanically to an auxiliary machine which controls the power transmitted through the rotary transformer.

3. A rotary transformer as claimed in claim 2 in which the auxiliary machine is electrically connected to at least one of the said circuits to interchange power therewith.

4. A rotary transformer as claimed in claim 2 or 3 in which the auxiliary machine is equipped with torque-controlling means for controlling the power through the rotary transformer.

5. A rotary transformer as claimed in claim 2 or 3 in which the auxiliary machine is a direct-current machine which has a constant excitation, so that its current is proportional to the power of the rotary transformer.

6. A rotary transformer as claimed in claim 2 or 3, in which the auxiliary machine is a non-synchronous machine which is fed from a converter that is so controlled that the flux of the auxiliary non-synchronous machine is constant.

7. A rotary transformer as claimed in claim 6 in which the power of the rotary transformer is regulated by controlling the current of the auxiliary non-synchronous machine.

8. A rotary transformer as claimed in claim 2 or 3 in which the auxiliary machine is a frequency-controlled synchronous machine.

9. A rotary transformer as claimed in claim 1 including for controlling the exchange of reactive power between the systems at least one transformer of adjustable transformation ratio connected between the non-synchronous machine and a system.

10. A rotary transformer as claimed in any of claims 2 to 8 in which oscillations of the non-synchronous machine are damped by controlling the auxiliary machine by means of measured values of operating parameters of the non-synchronous machine introduced into the regulating circuit of said auxiliary machine.

11. A rotary transformer, substantially as herein described with reference to Figure 1 and/or Figure 2 of the accompanying drawings.

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Fig. 1.

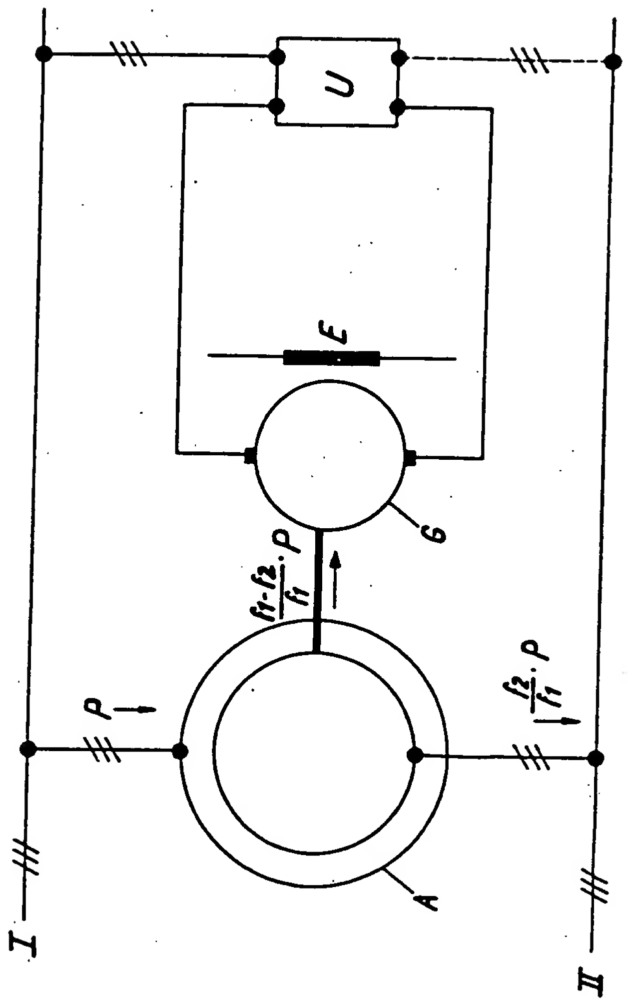

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Fig. 2